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8752 Characterization of Fracture Geometry and Roof Penetrations Associated with Stimulation Treatments in Coalbeds

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ABSTRACT

Twenty-two Government-sponsored stimulation treatments have been mined-through to determine the effects on the coalbed and roof strata. Vertical fractures in the coalbed were discernible for most treatments, and horizontal fractures were present in about half of the treatments. Sand-propped vertical fractures were usually short in lateral extent. Horizontal fractures were generally found within bedding planes, most commonly on top of the coalbed. Evidence of stimulation fluid movement could generally be traced beyond the maximum extent of sand-filled fractures when fluorescent paint was added to the treatment fluids. Penetration of strata overlying coalbeds was observed in nearly half of the treatments intercepted. Most of these occurrences have been interpreted to be penetrations into joints or other preexisting planes of structural weakness. No roof falls or adverse mining conditions were encountered that could be attributed to the stimulations.

INTRODUCTION

A total of 22 Government-sponsored stimulation treatments in coalbeds have been intercepted by mining. Twenty-one of these interceptions were in the Eastern United States (10 in Pennsylvania, 7 in Alabama, 2 in West Virginia, and 1 each in Illinois and Virginia); only one in the Western United States (Utah) was available for investigation. These underground interceptions have provided a unique opportunity to observe directly the actual effects of the stimulation treatments on coalbeds and surrounding strata. This report details observations previously presented in various forms by the Government and its contractors, as well as information not heretofore reported.

The Bureau of Mines has developed several techniques, including the use of horizontal and vertical boreholes, to remove gas from coalbeds in advance of mining. Horizontal boreholes drilled from underground workings as part of the mining cycle have been shown to be very effective in providing short-term, immediate relief from high methane emissions [1-6]. This technique has been widely accepted in the coal mining industry, but it does require close coordination to integrate the drilling and subsequent gas drainage and disposal into the mine development plan.

Vertical boreholes can be placed several years in advance of mining to predrain gas from coalbeds over relatively large areas [7-11]. The vertical borehole technique has the additional advantage over horizontal boreholes of allowing work to be performed on the surface instead of in the more restrictive underground environment. However, except for the relatively large scale vertical borehole programs for both mine safety and commercial gas production in the Black Warrior Basin of Alabama [7,9,11], the technique has been underutilized. The primary reason for this seems to be a combination of the economic conditions in the coal industry, legal questions as to the ownership of coalbed gas, and the fear of roof damage from the stimulation treatments. The question of potential roof damage is an important consideration addressed in this paper.

Underground evaluation of areas surrounding boreholes that have been stimulated to increase gas production from coalbeds is an important step in developing efficient stimulation treatments that do not adversely affect mining. By directly observing the effects of a particular stimulation design on a coalbed and surrounding strata and evaluating the observations in conjunction with thorough geologic characterization, valuable information can be obtained, especially early in the development stages of a methane drainage program. It is important to note that what is seen underground is dependent upon the area exposed by mining and the timing of observations in relation to the advance of entries. Obviously once a volume of coal is mined, anything contained in that coal is forever lost for direct examination.

Owing to the large amount of completion, treatment, and mine-through data associated with most of the stimulations, only a synopsis of the results from all the stimulations can be presented here. Additional detailed information can be obtained in the referenced publications, or in a new Bureau of Mines compilation and analysis of all pertinent data associated with the 22 treatments [12].

UNDERGROUND OBSERVATIONS

The underground observations have revealed a variety of conditions ranging from extensive vertical and horizontal sand-filled and/or fluorescent-paint-coated fractures to no discernible fractures. A summary of the treatment parameters and underground observations is given in tables 1 and 2. Eight of the treatments included the addition of fluorescent paint as an aid in locating and mapping the paths of fluid movement in the exposed coalbed and surrounding strata.

Vertical sand-filled fractures were generally wider nearest the borehole and narrowed rapidly away from the borehole. The maximum lateral extent of sand-filled vertical fracture wings was generally short. Nine boreholes had sand-filled fracture wings with a maximum length of 30 ft or less, three boreholes had fracture wings 70 to 100 ft in length, and only four (figs. 1, 2, and 3) had wings over 100 ft in length.

When fluorescent paint was used in the treatments, the fractures could usually be traced as paint-coated cleat beyond their maximum sand-filled extent. These cleat would not have been identified as a pathway for stimulation fluid without the presence of the paint. It is not known if the fractures represented by paint-coated cleat in fact represent paths of increased permeability that will enhance the flow of water and gas to the wellbore.

A good example of the additional traceable fracture length was observed at borehole DHM-6 (fig. 4) in the Blue Creek Coalbed, where sand-filled fractures could be traced a maximum of 95 ft (southwest) compared to paint-coated cleat observed 630 ft (northeast) from the borehole [17]. The paint-coated cleat at 630 ft are the longest observed evidence of stimulation fluid movement reported to date and was associated with one of the largest volume treatments. The most extensive paint-coated paths of fluid movement were observed in the vicinity of boreholes RP-2 and RP-3 in the Upper Freeport Coalbed (fig. 5) [19], and borehole TW-5 in the Blue Creek Coalbed (fig. 6) [9,16]. Fluid volume appeared to have some influence on the extent of fluid movement in that a greater number of fractures were associated with borehole RP-3, which had approximately a one-third larger volume treatment than RP-2. Borehole TW-5 also had one of the largest volume treatments.

Zones of multiple parallel sand-filled and/or paint-coated fractures are common near the boreholes. The use of paint was a significant aid in identifying multiple fluid pathways that were essentially only the width of a cleat (fig. 7). At increasing distances from the boreholes the number of multiple vertical fractures usually decreases and only a single fracture remains. Multiple fractures were somewhat more prevalent in the friable coalbeds like the Upper Freeport (fig. 7) and the Blue Creek (fig. 8). Blocky coalbeds like the Pittsburgh tended to have a predominance of single, wider, sand-filled fractures. These observations may be somewhat biased, however, since none of the treatments in the Pittsburgh Coalbed contained paint, and many of the zones of multiple fractures in the friable coalbeds were identifiable only as paint-coated cleat. This points out the need for caution when comparing observations from treatments with and without paint.

Vertical fractures commonly do not extend the entire height of the coalbeds, but are found only in part of the coalbed. In the Blue Creek Coalbed when fractures did not extend the entire height of the coalbed, they were usually present in the upper part, and less commonly, only in the lower part of the coalbed. This may be related to variations in the physical character of the Blue Creek Coalbed, which is commonly more friable and "soft" in the upper part.

Most of the observed sand-filled and paint-coated vertical fractures penetrated or paralleled face cleat and occasionally butt cleat in the coalbed. It is interesting to note that the longest sand-filled vertical fracture (416 ft, borehole 1-NE, Illinois No. 6 coalbed, fig. 3) did not parallel a cleat direction, but was approximately 30° from the butt cleat orientation [8]. This may result from the influence of local horizontal stress fields or unobserved stair-stepping along face and butt cleat which gave an apparent orientation oblique to the cleat orientation. At several locations, fractures that paralleled the face cleat did not directly intercept the borehole if extended back from their point of observation. Apparently these treatment fluids followed a "stair-step" pathway through the coalbed, with only the face cleat fractures being observed on the exposed ribs and pillars.

It has been suggested [9,20,21] that gelled water stimulation treatments with sand proppant would theoretically produce relatively short, wide, sand-filled vertical fractures and foam treatments would produce longer, narrow, sand-filled fractures. Only four of the treatments observed underground used gelled water as the treatment fluid, and therefore a definitive statement relating the relative differences between the character of fractures resulting from the different fluids is not possible. However, the widest sand-filled fracture observed (4-1/2 in, borehole TW-2, fig. 8) was from a gelled water treatment in the Blue Creek Coalbed [14]. A 2-1/2-in-wide sand-filled fracture was also observed for the gelled water treatment on borehole USBM-4 in the Pittsburgh Coalbed [8], but a 2-1/2-in-wide sand-filled fracture was also observed for the foam treatment on borehole EM-6 in the Pittsburgh Coalbed [9,10]. The longest sand-filled vertical fracture observed (416 ft, borehole 1-NE) was also from a gelled water treatment in the Illinois No. 6 Coalbed (fig. 3) [8], where short fractures might be expected.

A horizontal fracture was discernible in approximately half of the mined through stimulation treatments. Five of eight treatments that used fluorescent paint and seven additional treatments that did not use paint had identifiable horizontal fractures. It is generally thought that at increasing depths (overburden pressure) the incidence of horizontal fracturing decreases. A horizontal fracture was found in stimulated coalbeds as deep as 1,145 ft in the Blue Creek Coalbed (borehole TW-5, fig. 6) [9,16]. This fracture was only identifiable as paint coatings since no sand was used in the treatment on borehole TW-5. The two treatments with fluorescent paint in the Blue Creek Coalbed that did not have identifiable horizontal fractures were, at depths of 1,384 ft (borehole DHM-5) and 1,239 ft (borehole DHM-6), the deepest stimulations mined through [17]. The deepest stimulation with a sand-filled horizontal fracture was 1,093 ft in the Blue Creek Coalbed at borehole TW-2 [14]; however, the rest of the sand-filled horizontal fractures were found at depths of 400 to 800 ft. It seems likely that additional horizontal fractures (or fluid pathways) would have been observed, especially in the shallow coalbeds, if fluorescent paint had been used in more treatments.

The most common location for the horizontal fractures is at the top of the coalbed at the interface with the roof rock. Horizontal fractures are also found along other distinct interfaces such as shale partings, shaley or hard, dense bands in the coalbed, or at the bottom or top of rider coals in the immediate roof rock. The distribution of sand or paint on horizontal surfaces was generally erratic (partially because of the difficulty in mapping their entire area), but in two cases (boreholes RP-2 and RP-3) there was some suggestion that there was a correlation between cleat orientation and the axis of horizontal lobes of paint (figs. 9, 10) [19]. At borehole TW-5 [9,16] the horizontal (and vertical) fractures covered an area with a general elliptical shape with the long axis parallel to the face cleat orientation (fig. 6).

Multiple horizontal fractures on different planes have been observed in several cases. The sand-filled horizontal fractures are generally thickest near the wellbore (maximum of 1 in), usually are thin (less than 1/2 in) but quite variable in thickness along short lateral distances, and may be discontinuous along an exposed rib (fig. 11). The maximum lateral extents for sand-filled horizontal fractures were 250 ft in the Jawbone Coalbed (borehole DG-1A) [9] and 200 ft in the Upper Freeport Coalbed (borehole RP-3, fig. 10) [19]. The maximum lateral extents for paint-coated horizontal fractures were 265 ft and 200 ft in the Upper Freeport Coalbed (boreholes RP-2 and 3, figs. 9 and 10) [19] and 230 ft in the Blue Creek Coalbed (borehole TW-5, fig. 6) [9,16].

ROOF PENETRATION

Penetration by fluids and/or sand proppant into strata directly overlying the main bench of coal has been observed in nearly half of the treatments intercepted underground. In addressing the significance of roof penetration, it is necessary to point out that roof penetration does not necessarily equate to roof damage or an adverse effect on mining. There have been no roof falls attributed to the penetration of stimulation fluids into roof strata from Government-sponsored treatments. Lambert [9] did report that supplementary roof support was installed as a precautionary measure in the vicinity of borehole TW-3 at the Oak Grove Mine, where both the mined Blue Creek Coalbed and the overlying Mary Lee Coalbed 5-1/2 ft above were stimulated and where mine management observed "roof movement" along a nearby rib. According to Lambert [9], the area was mined through "without experiencing any roof fall during mining operations."

Except for the Blue Creek Coalbed, most of the penetrations of strata above the main coal bench have been fairly limited in vertical and/or horizontal extent. In several cases penetration of strata above the Blue Creek Coalbed was observed at locations a hundred feet or more from a borehole. The reason for the more extensive roof penetrations is not conclusively known, but may be related to the structural history of the area. Recent In Situ State of Stress (ISSOS) tests conducted near the Oak Grove Mine indicated lower in situ stress values for the rocks surrounding the Mary Lee-Blue Creek Coalbeds than measured in the coal [22]. In the absence of a stress barrier or mechanical property barrier, upward fracture breakout is more likely. Upward fracture breakout from this coal section was reported during the ISSOS testing near the Oak Grove Mine [22]. The presence of naturally occurring roof joints coupled with lower or similar in situ stresses above the coal probably influenced the extent of roof penetration at the Oak Grove Mine.

In several cases, the strata penetrated above coalbeds have been weak, thin shales below rider coals, and the fractures have been contained in strata that were generally mined along with the main bench of coal throughout the mine to prevent them from deteriorating and falling at a later time (fig. 12). Such strata penetrations should not really be considered "roof" penetrations; however, they are included as such in table 2.

Reluctance to accept the use of stimulated vertical boreholes to remove gas from coalbeds prior to mining may be related to the use of the terms "fracture," "fracturing," and "breakdown," which perhaps suggest a catastrophic breakup of the strata treated. The evidence from direct underground observation and many of the treatment records (including those from boreholes not mined through) suggests that "new" fractures are seldom created, but rather naturally occurring planes of weakness (cleat, joints, or bed boundaries) are entered and opened up to varying degrees. In most cases the penetration of strata overlying the main coal bench has been attributed to the invasion of preexisting joints, as evidenced by joints of the same general character and orientation occurring throughout a mine.

SUMMARY

The type of stimulation fluid probably has some influence on the character of the induced fractures, as do other factors such as treatment volume, injection rate, and depth and physical characteristics of the coalbed. Larger volume treatments tended to have more observable fractures, as was the case in the three progressively larger treatments in the Upper Freeport Coalbed (boreholes RP-1, 2, and 3, fig. 5). Boreholes TW-5 (fig. 6) and DHM-6 (fig. 4), which had two of the largest volume treatments, also had some of the most extensive networks of fractures.

The physical properties of the coalbed seemed to have some influence on the propagation of fractures. Many of the vertical fractures in the Blue Creek Coalbed were present only in the more friable upper part. The vertical sand-filled fractures at borehole TW-2 were located in the bottom "hard" part of the Blue Creek Coalbed and inclined and became horizontal at or near the interface between the lower "hard" part and the upper "soft" friable part (fig. 8). The Upper

Freeport Coalbed (boreholes RP-1, 2, and 3) had a distinct shale parting near the top of the coalbed. In some cases the parting acted as a barrier to the upward growth of fractures, as seen with most of the paint coated fractures shown in figure 7. But it was more common for the shale parting to be penetrated by the vertical fractures, which then became horizontal at the interface at the top of the parting and base of the upper coal bench (fig. 13). A distinct "shaley" band in the Pittsburgh Coalbed at borehole EM-8 was generally penetrated by the vertical fractures which continued vertical above it (fig. 14), but in one instance the fracture became horizontal above the band (fig. 15). It was also common to see small horizontal offsets in the vertical propagation of the fractures as different layers or bedding planes in the coalbed were encountered (fig. 14). These offsets occasionally resulted in an inclined or sinuous appearance to the "vertical" fracture. While the physical properties of the coalbed seemed to have some influence on the character of the fractures, that influence was variable and could not be considered predictable.

It is impossible to guarantee that a stimulation treatment in a coalbed will not adversely affect mining in some way. However, the underground evidence from the 22 case studies summarized in this report suggests that the probability of adversely affecting mining conditions is minimal. The use of pre-stimulation strata characterization tests, informed treatment design, and controlled treatment implementation (primarily injection rates and therefore treatment pressure) can probably further minimize the chance of adverse mining conditions.

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TABLE 1. - Summary of data for 22 intercepted stimulation treatments

Coalbed, Mine, Borehole	Depth to Top of Coal (ft)	Treatment Type	Treatment Fluid: Volume (gal)	Treatment Fluid: Injection Rate (BPM)	Sand Weight, (lb)	Surface Pressure (psig): Average	Surface Pressure (psig): Maximum
Blue Creek Coalbed, Oak Grove Mine, Jefferson County, Alabama							
TW-1 [13]	1,113.0	Gel/Water	5,290	2-10.5	2,500	650	1,775
TW-2 [14]	1,093.4	Gel/Water	3,500	8	4,000	2,400	2,500
TW-3 [15]	1,074.0	Foam	20,000	10	25,000	1,400	1,500
TW-4 [16]	1,065.0	Foam	12,200	10	12,520	1,500	1,800
TW-5 [9,16]	1,145.0	Foam	53,000	2-6	-	1,900	2,000
DHM-5 [17]	1,383.5	Foam	40,866	7	-	850	950
DHM-6 [17]	1,238.6	Foam	50,568	3-7	10,000	850	900
Pittsburgh Coalbed, Vesta No. 5 Mine, Washington County, Pennsylvania							
USBM-4 [8]	588.0	Gel/Water	7,300	10.5	3,500	1,550	1,800
Pittsburgh Coalbed, Emerald Mine, Greene County, Pennsylvania							
EM-5 [9,10]	764.0	Foam	31,500[a]	11.6	10,000	1,375	NR
EM-6 [9,10]	582.0	Foam	29,200[a]	17.7	14,000	1,500	2,150[b]
EM-7 [9,10]	728.0	Foam	29,000[a]	10.8	7,400	1,400	NR[b]
EM-8 [10]	646.0	Foam	42,000[a]	10.8	12,800	1,050	1,200
EM-11 [9]	713.0	Kiel-Water	54,600	19	10,000	1,200	NR
Pittsburgh Coalbed, Cumberland Mine, Greene County, Pennsylvania							
CNG-1034 [18]	754.0	Foam	21,840[c]	10	23,500	1,200	NR
Upper Freeport Coalbed, Lucerne No. 6 Mine, Indiana County, Pennsylvania							
RP-1 [19]	626.5	Water	1,600	.4-7.4	-	-	1,260
RP-2 [19]	630.4	Foam	19,800	8	7,000	1,150	1,250
RP-3 [19]	634.6	Foam	30,200	6	11,500	850	1,110
Lower Kittanning Coalbed, Kitt No. 1 Mine, Barbour County, West Virginia							
KE-2 [19]	660.0	Foam	23,500	8	3,300	-	2,000[b]
DGBM-5	637.3	Foam	50,400	8	11,800	950	1,210
Illinois No. 6 Coalbed, Inland, Steel Mine Jefferson County, Illinois							
1-NE [8]	729.0	Gel/Water	12,000	10	6,400	850	1,050
Jawbone Coalbed, McClure No. 1 Mine, Dickenson County, Virginia							
DG-1A [9]	425.0	Foam	35,300[d]	16	28,000	NR	NR
Rock Canyon Coalbed, Soldier Canyon Mine, Carbon County, Utah							
SC-1 [19]	684.0	Foam	50,000	16	15,000	1,350	1,500

[a]Plus 900-gal water pad.
[b]Screenout occurred.
[c]Plus 640-gal water flush.
[d]Plus 4,200-gal water pad.

TABLE 2 - Summary of underground observations for 22 intercepted stimulation treatments

Borehole	Hole Location Exposed	Fluorescent Paint Used	Maximum Observed Vertical Wing Length (ft): Sand-Filled	Maximum Observed Vertical Wing Length (ft): Paint Coated	Maximum Vertical Fracture Width (in)	Zones of Multiple Vertical Fractures	Maximum Observed Horizontal Fracture Length (ft): Sand-Filled	Maximum Observed Horizontal Fracture Length (ft): Paint-Coated	Multiple Horizontal Fracture Planes	Roof Penetration
TW-1	Yes	No	5	-	1/2	Yes	-	-	-	Yes
TW-2	Yes	No	16	-	4-1/2	Yes	8	-	Yes	No
TW-3	Yes	No	210	-	3/16	No	-	-	-	Yes
TW-4	Yes	No	220	-	3/16	No	-	-	-	Yes
TW-5	Yes	Yes	-	370	Cleat	Yes	-	230	Yes	Yes
DHM-5	No	Yes	-	340	Cleat	Yes	-	-	-	Yes
DHM-6	Yes	Yes	95	630	1/16	Yes	-	-	-	Yes
USBM-4	Yes	No	20	-	2-1/2	Yes	-	-	-	No
EM-5	No	No	140	-	1-1/2	No	50	-	No	No
EM-6	Yes	No	10	-	2-1/2	Yes	10	-	Yes	Yes
EM-7	Yes	No	18	-	1/2	No	-	-	-	No
EM-8	No	No	55	-	3/16	Yes	115	-	Yes	Yes
EM-11	No	No	-	-	-	-	110	-	No	Yes
CNG-1034	No	No	100	-	1/4	No	-	-	-	No
RP-1	Yes	Yes	2[a]	2	1/16	Yes	-	35	No	No
RP-2	Yes	Yes	30	67	1/2	Yes	17	265	Yes	No
RP-3	Yes	Yes	20	130	1	Yes	200	200	Yes	No
KE-2	No	Yes	-	85	Cleat	No	-	100	No	No
DGBH-5	No	No	72	-	1/2	Yes	105	-	No	No
1-NE	No	No	416	-	3/8	No	-	-	-	Yes
DG-1A	Yes	No	20	-	5/8	-	250	-	Yes	No
SC-1	No	Yes	-	-	-	-	-	-	-	-

[a]Sand from fill at bottom of hole not from treatment.

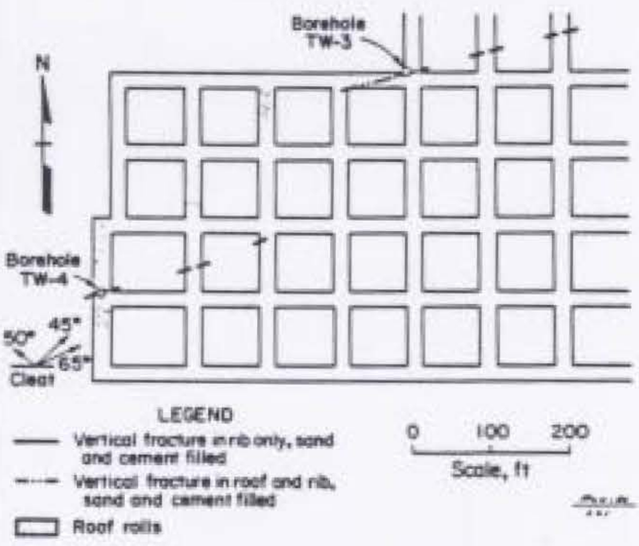

FIGURE 1. - Mine map, boreholes TW-3 and TW-4, with fracture orientations. (Modified from Lambert [15])

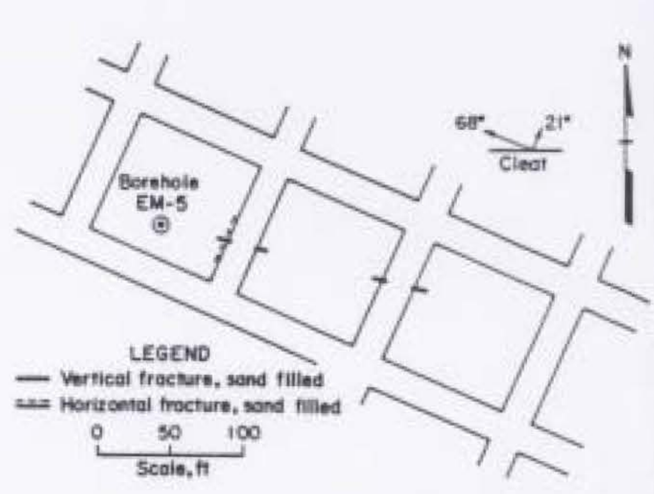

FIGURE 2. - Mine map, borehole EM-5, with fracture orientations. (Modified from Lambert [9])

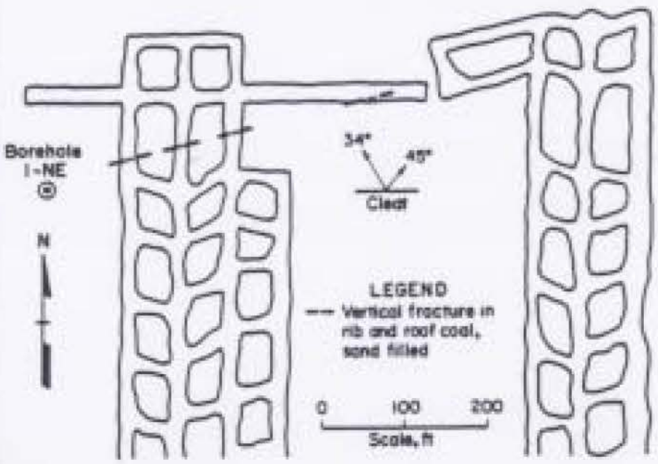

FIGURE 3. - Mine map, borehole 1-NE, with fracture orientations. (Modified from Elder [8])

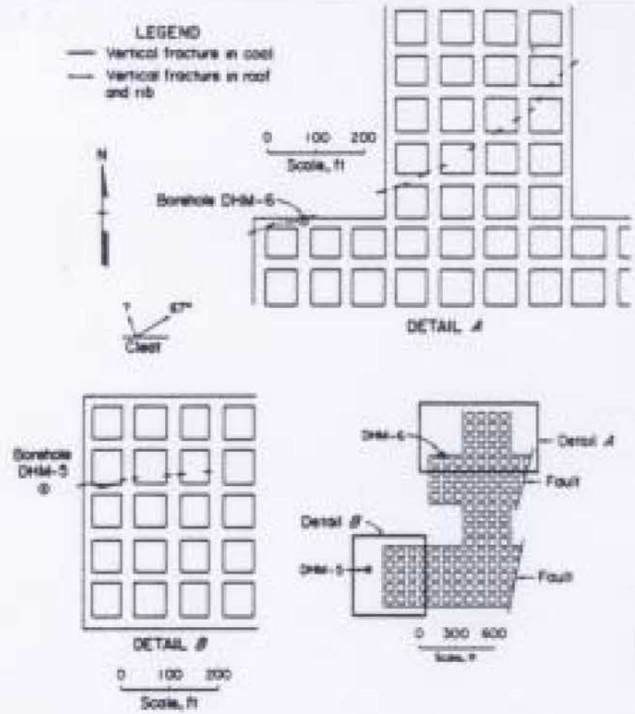

FIGURE 4. - Mine map, boreholes DHM-5 and DHM-6, with fracture orientations. (Modified from Boyer [17])

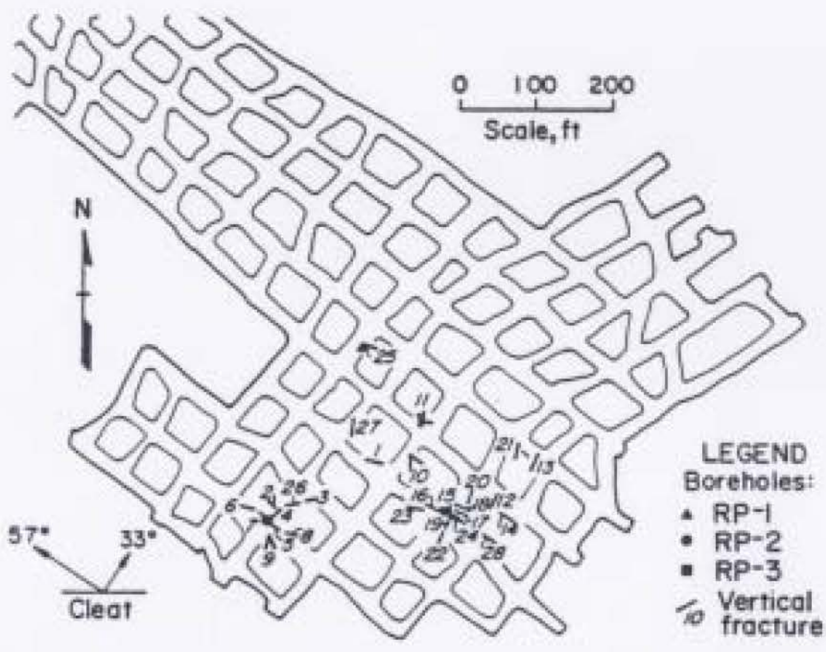

FIGURE 5. - Mine map, boreholes RP-1 through RP-3, with fracture orientations [19].

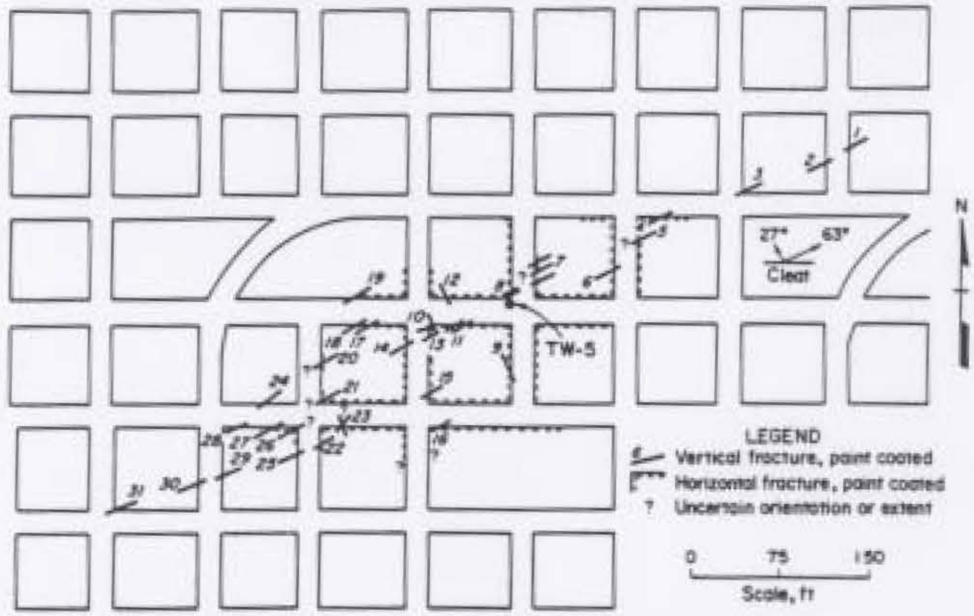

FIGURE 6. - Mine map, borehole TW-5, with fracture orientations. (Modified from Mahoney [16])

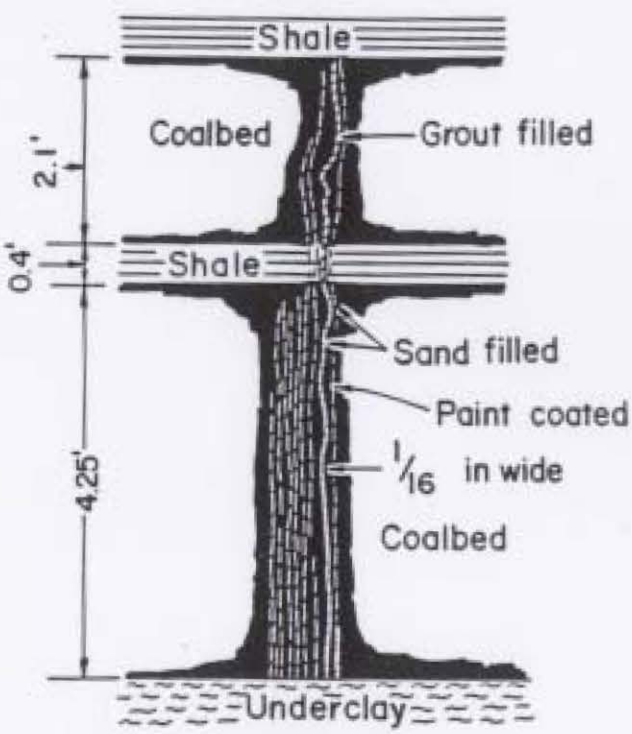

FIGURE 7. - Cross section of fractures at location 25 on the southeast rib near borehole RP-1. (Modified from Murrie [19])

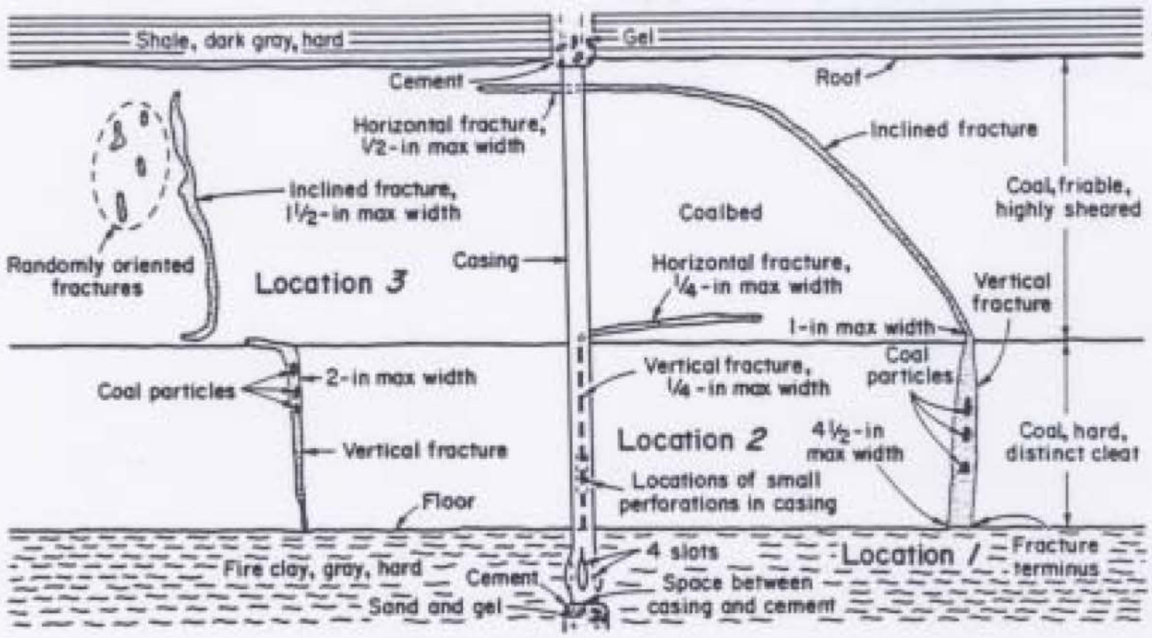

FIGURE 8. - Cross section of coal face at borehole TW-2 with fracture orientations. (Modified from Lambert [14])

FIGURE 9. - Mine map, boreholes RP-1 through RP-3, with horizontal distribution of paint on roof [19].

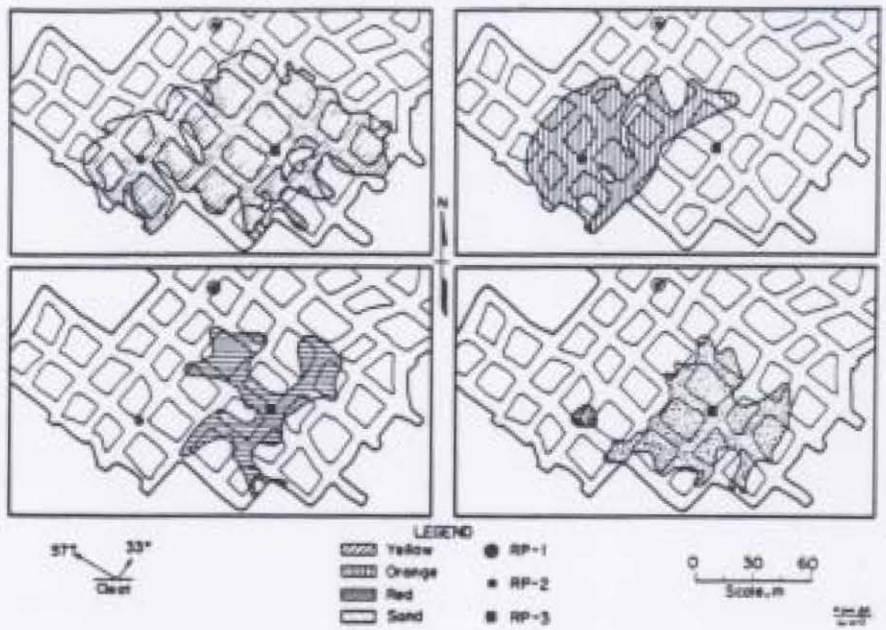

FIGURE 10. - Mine map, boreholes RP-1 through RP-3, with horizontal distribution of paint and sand on top of shale parting [19].

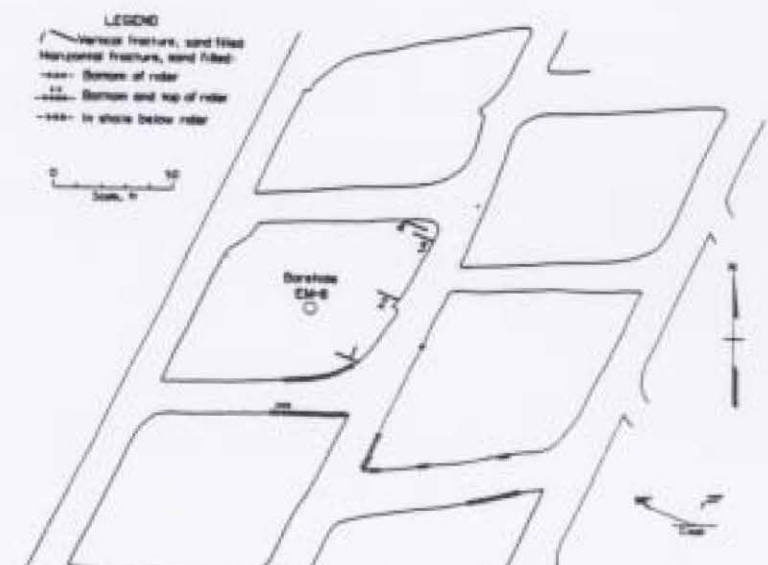

FIGURE 11. - Mine map, borehole EM-8, with fracture orientations.

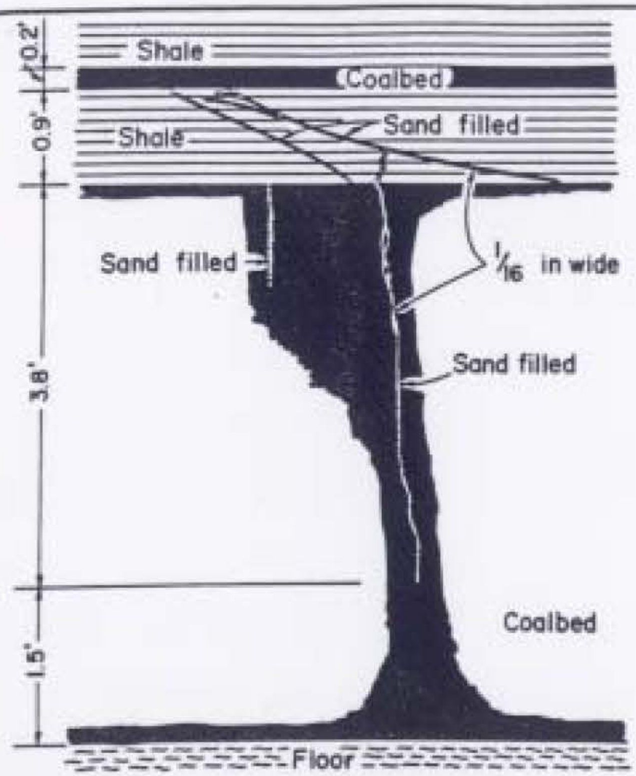

FIGURE 12. - Cross section of fractures on rib at location 1 near borehole EM-8.

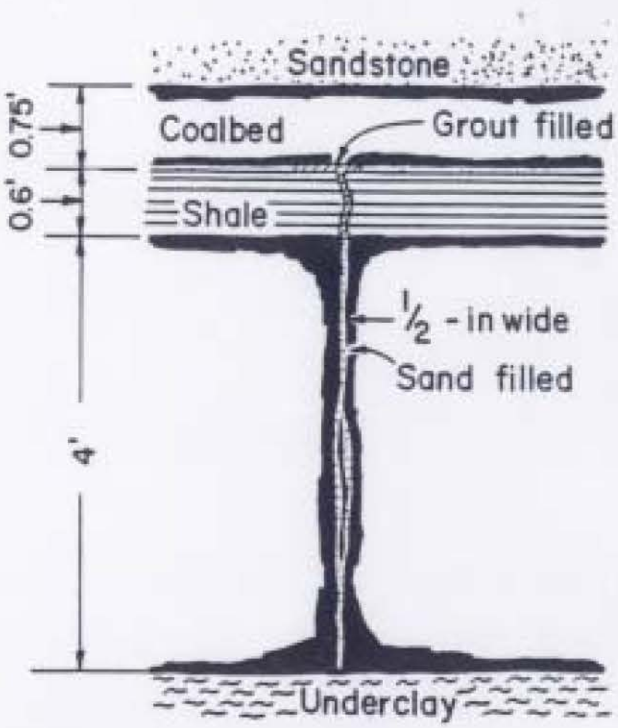

FIGURE 13. - Cross section of fractures at location 7 near borehole PR-2. [19]

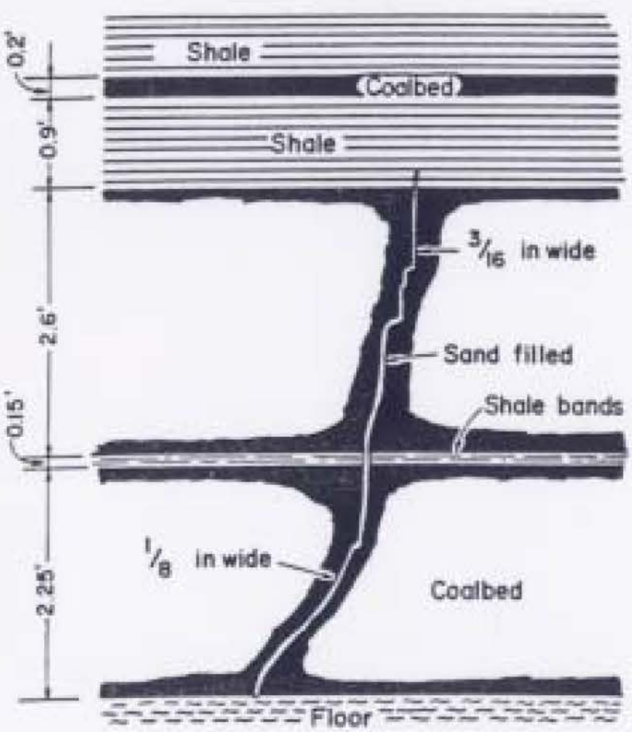

FIGURE 14. - Cross section of fracture on rib at location 4 near borehole EM-8.

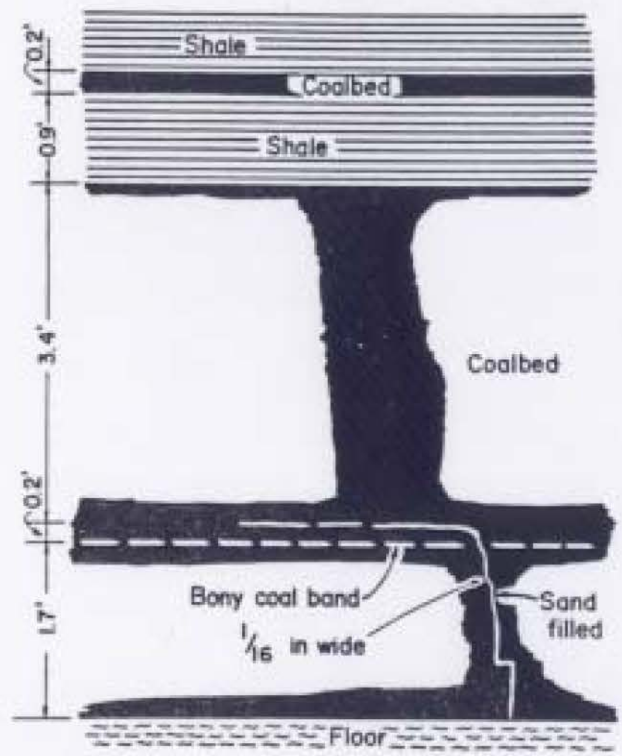

FIGURE 15. - Cross section of fracture on rib at locaton 2 near borehole EM-8.